AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Biogeosciences

RESEARCH ARTICLE

10.1002/2017JG004267

Key Points:
- Assisted natural regeneration forests significantly reduced surface runoff and sediment yield
- Assisted natural regeneration forests significantly increased plant diversity
- Assisted natural regeneration forests have the potential to store tremendous amount of carbon in aboveground biomass

Supporting Information:
- Supporting Information S1

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Citation:
Yang, Y., Wang, L., Yang, Z., Xu, C., Xie, J., Chen, G., et al. (2018). Large ecosystem service benefits of assisted natural regeneration. *Journal of Geophysical Research: Biogeosciences*, *123*, 676–687. https://doi.org/10.1002/2017JG004267

Received 4 NOV 2017
Accepted 31 JAN 2018
Accepted article online 13 FEB 2018
Published online 28 FEB 2018

Large Ecosystem Service Benefits of Assisted Natural Regeneration

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Abstract China manages the largest monoculture plantations in the world, with 24% being Chinese fir plantations. Maximizing the ecosystem services of Chinese fir plantations has important implications in global carbon cycle and biodiversity protection. Assisted natural regeneration (ANR) is a practice to convert degraded lands into more productive forests with great ecosystems services. However, the quantitative understanding of ANR ecosystem service benefits is very limited. We conducted a comprehensive field manipulation experiment to evaluate the ANR potentials. We quantified and compared key ecosystem services including surface runoff, sediment yield, dissolved organic carbon export, plant diversity, and aboveground carbon accumulation of ANR of secondary forests dominated by *Castanopsis carlesii* to that of Chinese fir and *C. carlesii* plantations. Our results showed that ANR of *C. carlesii* forest reduced surface runoff and sediment yield up to 50% compared with other young plantations in the first 3 years and substantially increased plant diversity. ANR also reduced the export of dissolved organic carbon by 60–90% in the first 2 years. Aboveground biomass of the young ANR forest was approximately 3–4 times of that of other young plantations, while aboveground biomass of mature ANR forests was approximately 1.4 times of that of mature Chinese fir plantations of the same age. If all Chinese fir plantations in China were replaced by ANR forests, potentially 0.7 Pg more carbon will be stored in aboveground in one rotation (25 years). The results indicate that ANR triggers positive feedbacks among soil and water conservation, biodiversity protection, and biomass accumulation and thereby enhances ecosystem services.

Plain Language Summary China manages the largest monoculture plantations in the world, with Chinese fir plantation being the world's most important plantation by acreage. Ecosystem services of the forest plantations largely depend on the management practices undertaken. Assisted natural regeneration (ANR) has been suggested to have a tremendous potential to enhance forest ecosystem services, but quantitative analyses of the ANR potentials are rare. We conducted a comprehensive field manipulation experiment to compare key ecosystem services of ANR of secondary forests dominated by *Castanopsis carlesii* to that of Chinese fir and *C. carlesii* plantations. Our results showed that compared with other young plantations, ANR of *C. carlesii* forest reduced surface runoff and sediment yield by ~50%, reduced the export of dissolved organic carbon by 60–90%, and substantially increased plant diversity. Aboveground biomass of the young ANR forest was approximately 3–4 times of that of other young plantations, while aboveground biomass of mature ANR forests was ~1.4 times of that of mature Chinese fir plantations. This first comprehensive ANR study clearly illustrates tremendous potential of ANR in enhancing ecosystem services of forest plantations.

1. Introduction

Although globally deforestation rate is high at a rate of ~13×10^6 ha yr^{-1} in the first decade of the 21st century, forest plantation area has increased by 5×10^6 ha in the same period, with the global forest plantations being 264×10^6 ha or 7% of the global forest area by 2010 (Food and Agriculture Organisation of the United

Nations, 2005). Forest ecosystems provide a number of important ecosystem services (Millennium Ecosystem Assessment, 2005), such as carbon sequestration, biodiversity protection, and soil and water conservation. However, it is generally agreed that ecosystem services provided by plantations do not match those of original natural forests (Chazdon, 2008). Plantation management practices differ in their effect on ecosystem services. Therefore, a major effort of plantation management focuses on maximizing ecosystem services (Chazdon, 2008).

China manages the greatest acreage of monoculture plantations in the world, ~70×10^6 ha by 2013 (State Forestry Administration, 2014). Most of the forest plantations were originally natural forests that were directly or indirectly (i.e., converted to other land uses in the past) converted to plantations (Thomson, 2009). Chinese fir, *Cunninghamia lanceolata* (Lamb.) Hook (Taxodiaceae), is the most important plantation tree species by area both in China and the globe, contributing 17×10^6 ha or 24% of the forest plantations in China and 6.3% of the globe (Del Lungo et al., 2006). Chinese fir is widely planted because of its high growth rate, with an average annual increment in height, diameter, and volume of 1 m, 1 cm, and 1 m^3, respectively (Li, 1992), and high wood quality desirable for furniture and constructions (Duan et al., 2016). The large area of Chinese fir plantation in China was a result of the replacement of many nature broadleaf forests such as the Chinquapin, *Castanopsis carlesii* forests. A number of studies have documented negative impacts of monoculture Chinese fir plantations regarding soil fertility, surface runoff, sedimentation, and carbon budget (Bi et al., 2007; Chen et al., 2016; Tian et al., 2008; Yang, 1998; Yang et al., 2003, 2007).

Soil erosion and the subsequent sediment transport through runoff is an important environmental problem for its effects on water quality and on organic carbon transport (Liu et al., 2008). Some forest management practices such as land clearing, and road and trail construction can accelerate erosion processes, especially in regions with rough topography (Sidle et al., 2006). The distribution of Chinese fir plantations concentrates on the humid and hilly southeastern China (Zhou et al., 1981) where the potential of erosion and sediment production is among the highest in China (Lal, 1990). A total area of 870,000 km^2, 74% of the total area of Southern China Hilly Region, was designated as "Erosion Survey Zone," with an average erosion rate of ~3,420 t km^{-2} yr^{-1}, that requires erosion control measures (Liang et al., 2008).

A recent global assessment concludes that primary forests are irreplaceable for sustaining tropical biodiversity and large-scale forest inventories reveal positive effects of tree diversity on productivity (Gibson et al., 2011). Regionally, a recent study highlights the importance of establishing mixed-species plantations for diversity conservation and improvement of ecosystem functioning in subtropical China (Yang et al., 2013). However, several studies have reported decreasing biodiversity with increases in plantation area in tropical and subtropical China (Williams, 2015; Zhai et al., 2014). Thus, enhancing biodiversity in forest plantations should be of high priority in forest management, particularly in southeastern China.

Forest ecosystems accounting for more than 70% of global terrestrial carbon are the most important terrestrial carbon sink (Dixon et al., 1994; Litton et al., 2007; Pan et al., 2011). Afforestation and reforestation have a great potential to increase carbon storage (Fang et al., 2001; Ravindranath et al., 2008; Schulze et al., 2000). However, the effectiveness of managing forest plantations for carbon sequestration has been challenged (Law et al., 2003; Schulze et al., 2000) and its success largely depends on the ecological understanding of the forests (Chazdon, 2008).

Assisted natural regeneration (ANR) or near-natural regeneration is a simple and inexpensive practice for converting degraded lands to more productive forests (Shono et al., 2007). Through minimizing barriers to natural regeneration such as soil degradation, competition with weedy species, and recurring disturbances by fire, grazing, and wood harvesting, ANR is applied to accelerate, but not to replace, natural regeneration (Shono et al., 2007). ANR has been practiced in several countries in Asia for approximately four decades (Ganz & Durst, 2003; Shono et al., 2007) and has been known in China for more than five decades (Sannai, 2003; Shao et al., 1960; Wang & Guan, 1958; Yao & Wang, 1988). The exact practices of ANR vary from one location to another. While there is not a unified definition of ANR, the most fundamental practices of ANR are protecting and facilitating the growth of parent trees inherently present in the area and their regenerations, rather than establishment of entire new monoculture plantations (Dugan et al., 2003; Shoo & Catterall, 2013).

In China, based on site quality there are two major types of ANR. In the degraded areas, the site is preserved without any management for several years and management practices such as weeding and thinning are applied only after the vegetation has substantially recovered (Dugan et al., 2003; Li, 1985). In more fertile sites, such as our study site, ANR begins when the existing forests are harvested (Dugan et al., 2003; Li, 1985). ANR is distinctively different from traditional management of Chinese fir plantations, in which slash burning is applied followed by site preparation (tilling strips/the entire field or digging trenches/pits) prior to planting Chinese fir seedlings. Then weeding is conducted twice a year for the first 3 years, thinning is conducted at around 8 years, and finally, the plantation is harvested at the age of approximately 25–50 years, followed by another cycle of planting (Yang, 1998). Despite of the great environmental potentials, ANR is not widely applied across the globe, possibly due to lack of demonstrated positive results (Shono et al., 2007).

Several studies have reported that ANR enhances biodiversity, forest productivity, tree growth, and carbon sequestration (Brown et al., 1996; Chazdon et al., 2016; Poorter et al., 2016; Stone, 2009). However, to date, almost all the studies were based on comparisons between existing forests with assumed similar geological, morphological, and pedological settings and land use history. The lack of manipulation studies with a rigorous experimental design cannot rule out the effects of factors other than differences in forest management. To quantitatively and directly evaluate the effects of ANR on key ecosystem services, in the current study, we present results from a forest manipulation experiment using experimentally established forest stands in combination with data from a mature ANR forest dominated by *C. carlesii* and a mature Chinese fir plantation in the same site to explicitly test the effects of ANR on forest carbon storage, plant diversity, and watershed erosion protection.

2. Materials and Methods

2.1. Study Site

The study site was located at Sanming City, Fujian Province, China. The area is dominated by low mountains and hills with an average elevation of 300 m and slope steepness of 25°–45°. The soils, which often exceed 1 m, were developed from biotite granite, with a carbon content of 22.7 g kg^{-1}, nitrogen content of 1.4 g kg^{-1}, dissolved organic carbon (DOC) content of 56 mg kg^{-1}, and bulk density of 1.04 g cm^{-3}, and can be classified to sandy clay Ferric Acrisol according to the Food and Agriculture Organisation of the United Nations/United Nations Educational, Scientific and Cultural Organization classification system, equivalent to Hapludults in the United States Department of Agriculture Soil Taxonomy (Lü et al., 2015). The organic layer is usually less than 10 cm. Subtropical evergreen broadleaved forests are the dominant natural vegetation of this area. This region has a typical maritime subtropical monsoon climate. The annual mean temperature is 20.1°C, and mean annual rainfall is 1,670 mm between 1959 and 2006, with approximately 80% occurring between March and August.

The experiment was conducted at a state-owned forest farm of Chenda of Sanming City, established in 1958. Prior to 1958, the area was covered by natural broadleaf forests dominated by *C. carlesii*. Since 1958, the natural forests were gradually logged and replaced by plantations (mainly Chinese fir) and naturally regenerated forests with minimal assistance (i.e., ANR). The selected study site was an ANR forest (hereafter referred as mature ANR forest) that was converted from a natural forest in 1976. In our study, ANR began with carefully maintaining seedlings of dominant tree species of the area during logging, no slash burning following logging the mature forest (instead, the residues were evenly redistributed in the ANR plots) and no tilling or weeding in the first 2 years. In July 2014, overgrown vines and *Scleria elata* Thw., *Gahnia tristis* Nees, and *Miscanthus floridulus* (Lab.) ex Schum. et Laut. were removed, which was different from the weeding of all plants other than the planted species in the young plantations. After the first 3 years, overcrowded sprouts were thinned in October 2015. Weeding will be applied in 2020, but there will be no thinning around 8 years, which is commonly applied in conventional management of Chinese fir plantations.

2.2. Experimental Setup

In 2011, an area of 1.1 ha within the mature ANR forest was selected for a runoff experiment (Figure 1). The runoff experiment comprises a total of fifteen 20 m × 5 m plots distributed among five treatments. Nine of the 15 plots in which logging was done were randomly assigned to the three treatments, young ANR treatment, young *C. carlesii* treatment, and young Chinese fir plantation treatment, using a randomized block design. Of the remaining six plots, three were mature ANR plots, located in one slope adjacent to the northeast edge of

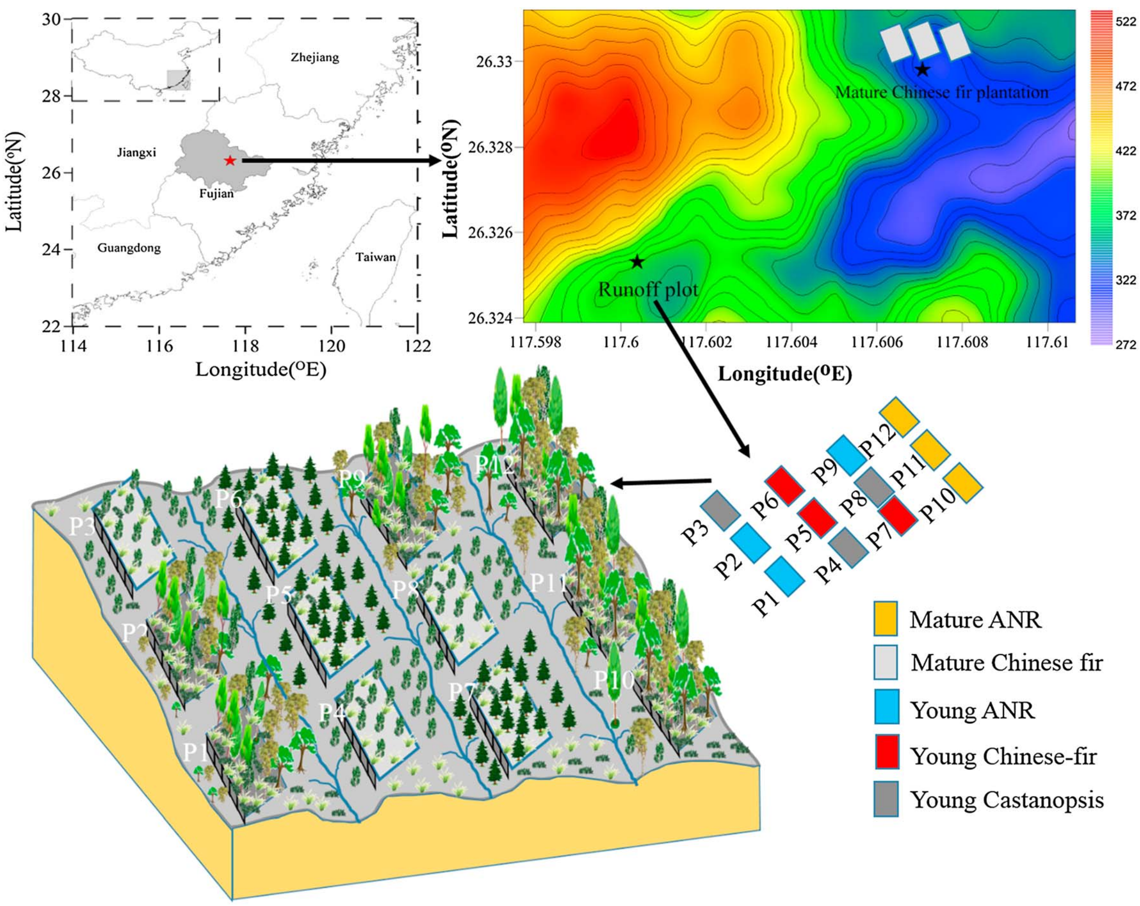

Figure 1. Location of the study site and experimental layout of the study.

the logging plots, and another three were mature Chinese fir plantations, located 600 m northeast to the logging plots. In the young ANR treatment, seedling from sprouting and seeds were conserved at a density of 4,,500–6000 seedlings per hectare in December 2011 (Figure 2a). Prior to the logging, a comprehensive vegetation survey was conducted (results listed in Tables S1 and S2 in the supporting information). Following traditional stem-only harvest, the bole wood was removed and branches, twigs, and leaves were retained and evenly spread over the logged land. Seedlings sprouted from tree stumps, and soils were carefully conserved in the first 3 years and then left for the development of secondary forest through succession. In the young Chinese fir plantation treatment, the mature ANR forest was also clear cut in December 2011 and harvested. Residues (branches, twigs, and leaves) of the same amount as in the young ANR were evenly spread over the land. After a 3 month exposure, the residues were burnt (Figure 2b) in March 2012 followed by planting Chinese fir seedlings at a density of 2,860 seedlings per hectare based on a widely accepted recommendation (Lin et al., 1996). Following the common practice for Chinese fir plantations, weeds were cut with wood chopper twice a year (Figure 2c), one in June–July and the other in November–December in the first 3–5 years depending on levels of canopy closure (i.e., when canopy was closed and weeding stopped). In the young *C. carlesii* treatment, the treatment was exactly like young Chinese fir plantation, except that instead of Chinese fir, seedlings of *C. carlesii* were planted at a density of 2,400 seedlings per hectare. The nine treated plots (three plots for each treatment) were laid out in three randomized blocks (Figure 1). The three treatments were also applied in adjacent forests for destructive biomass measurements. For the two mature forests, the mature ANR was used as control in which the mature ANR forest was left untreated. The mature Chinese fir plantation, followed the traditional management of Chinese fir plantations, was used for comparison with the mature ANR forest. Both mature forests were converted from a natural *C. carlesii* forest in the same year.

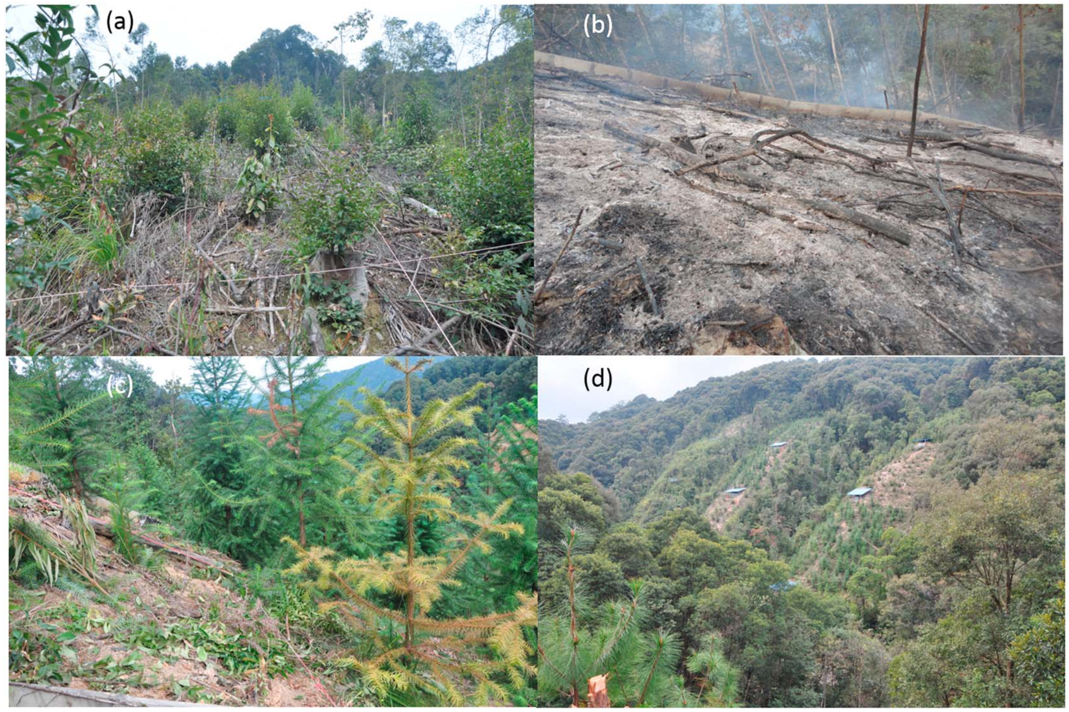

Figure 2. Sprouts of *Castanopsis carlesii* and plant residues are kept in assisted natural regeneration of *C. carlesii* forests (a). In contrast, in the traditional management of Chinese fir plantations, natural *C. carlesii* forests are burnt (b), and seedlings of Chinese fir were planted followed by weeding in the first 3–5 years (c). The differences in management results in very different vegetation growth in the first few years (photograph taken 2 years after the treatment) (d).

2.3. Runoff Sampling

To monitor runoff from the three young forests and the two mature forests, a stainless steel tank was constructed at the bottom of each of the 15 runoff plots. A trough with a depth of 190 cm and a mouth width of 45 cm was used to direct runoff from the plot to the tank. The dimension of the tank is 2 m (length) × 1 m (width) × 1 m (height) for the three young forests and 1 m × 1 m × 1 m for the two mature forests. Runoff water and sediment from each plot were sampled after each erosive rainfall event (i.e., with runoff in the steel tank). A time interval of 6 h was adopted to divide two rainfall events. After each erosive rainfall event, water depth in each tank was measured and recorded, followed by a thorough stirring to assure full mix of the suspended sediment with runoff water, and then, a 1.5 L sample was taken using a 1.5 L polyethylene bottle. Following the sampling, the water and suspended sediment were discharged. The tank was then cleaned, bed load sediment deposited in the tank weighed, and three 2000 g samples taken for determination of water, carbon, and nitrogen content. The monitoring of runoff started in April 2012, and results of the first 3 years were used in this study (i.e., April 2012 to March 2015).

2.4. Runoff Volume and Sediment Yield

Runoff volume, expressed as $m^3\ ha^{-1}$, was determined by multiplying water depth with the area of the tank. Total sediment of each erosion event was determined by adding up the suspended sediment and bed load sediment. For each 1.5 L water sample, we took a 100 mL subsample for chemical analysis, and the rest of it was oven dried at 65°C to determine the quantity of suspended sediment, which was used to estimate total suspended sediment in the tank by multiplying the content by the total runoff volume. The total bed load sediment was estimated by multiplying the wet mass of bed load sediment cleaned out from the tank by water content of bed load determined by the 2,000 g samples. DOC concentrations of runoff water were determined using a TOC-VCPH/CPN analyzer (Shimadzu Corporation, Kyoto, Japan).

2.5. Species Diversity Investigation

Three 20 m × 20 m quadrats were laid out in both the mature ANR forest and mature Chinese fir plantation. Each quadrat was divided into sixteen 5 m × 5 m subplots. Each young forest plot was divided into sixteen

2.5 m × 2.5 m subplots. All plants within each subplot were recorded and identified to species. Some woody plants could be either trees or shrubs, particularly in the young forests in which the woody plants were generally small. However, shrubs rarely grow more than 3 m. Therefore, to avoid confusion and to better reflect structural complexity, instead of classifying the plants into trees, shrubs, and herbaceous plants, we classified them into three layers by height: tree layer (≥3 m), shrub layer (1–3 m), and herbaceous layer (<1 m). The survey was conducted in October 2010 for the two mature forests and in October 2015 for the three young forests.

From the survey data, we calculated species richness (S) and exponential of Shannon entropy (Exp(H′)) (Jost, 2006) for each layer.

$$\mathrm{Exp}\left(H^{'}\right) = \mathrm{Exp}\left(-\sum_{i=1}^{s} P_i \ln P_i\right), \tag{1}$$

where P_i is the relative abundance of each species and the *s* is the total number of species.

2.6. Biomass Estimation

The biomass of the mature ANR forest was taken from a previous study, which used allometric models to determine biomass in 2010 (Lin et al., 2016). Biomass of trees in the mature Chinese fir plantation was estimated by allometric model, which was expressed as:

$$B_i = a\left(\mathrm{DBH}^2 \times H\right)^b, \tag{2}$$

where B_i is the biomass of tree component *i*, *a* and *b* are fitted parameters, DBH is the diameter at breast height, and *H* is the tree height.

In 2010, three 20 m × 20 m permanent plots within the mature Chinese fir forest were established to measure the DBH and height of all trees, including both Chinese fir and other tree species (Table S3). Based on the DBH distribution, we selected and felled 23 Chinese fir trees and 18 trees of other species outside our plots (Table S4) to build two allometric equations, one for Chinese fir and the other for the rest of the species. Three 2 m × 2 m subplots were established in each plot, and all understory vegetation and litter were collected and weighed.

Allometric models were used to estimate biomass of woody plants taller than 1 m for the young ANR forest. *Castanopsis carlesii*, *Litsea cubeba*, and *Sapium discolor* were the three dominant species contributing 67.4% of total basal area of all woody plants. We established an allometric model for each of the three dominant species and one allometric model for all other species. Twenty-two sample trees for *C. carlesii*, 19 for *L. cubeba*, 24 for *S. discolor*, and 23 for the rest of the species that covered a wide range of basal area were chosen for establishing the models. Fresh mass of leaves, branches, and stems (including barks) were measured, and then tree components were sampled to determine water content by ovendrying at 65°C.

Here the same form as equation (2) was used to establish allometric models for biomass estimation of young woody plants. Because young woody plants had very small DBH, we used diameter at stem base instead:

$$y_i = a\left(\mathrm{SBD}^2 \times H\right)^b, \tag{3}$$

where y_i is the biomass of tree component *i*, *a* and *b* are fitted parameters, SBD is the stem base diameter, and *H* is the tree height.

Biomass of herbaceous plants and woody plants lower than 1 m of the young ANR forest were estimated by whole harvest method. Three 1 m x 1 m subplots were set up in each 20 m x 5 m plot and all herbaceous and shrub plants were harvested and weighed. Subsamples were taken, weighed, and ovendried and weighed again.

The biomass of young *C. carlesii* and Chinese fir and understory vegetation was estimated using the same approach for the estimation of the biomass of the young ANR forest. Biomass of other tree species was low and estimated using the mixed allometric equation. The stem base diameter and height of each sample tree were listed in Tables S5–S8.

2.7. Data Analysis

We used two-way analysis of variance to examine the effects of two independent variables (forest types and treatment year) on three dependent variables (runoff, sediment yield, and DOC export). Because the interactions between treatment year and forest types were significant for two of the three variables (i.e., sediment

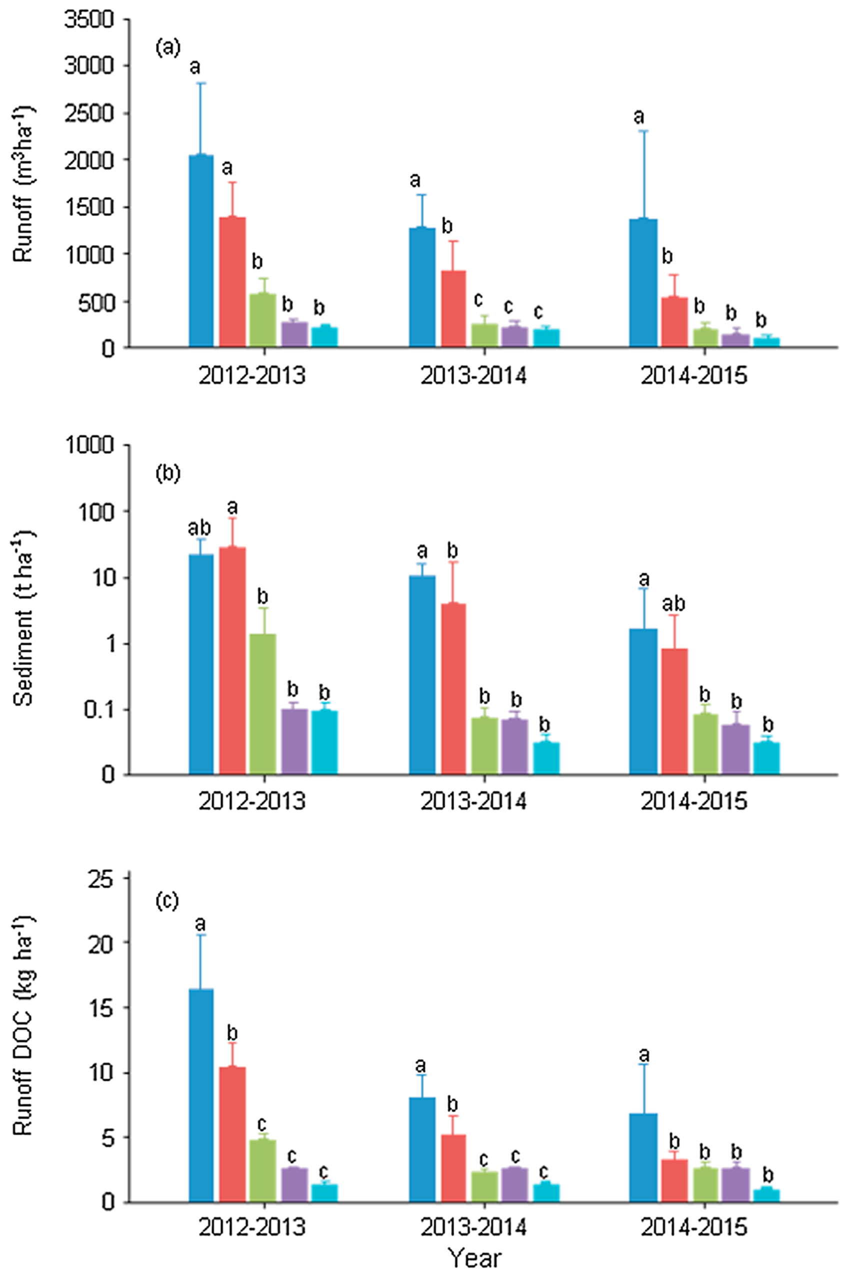

Figure 3. Runoff (a), sediment yield (b), and dissolved organic carbon export (c) of three young and two mature forests. Bars of the same group sharing no common letter are statistically different (one-way analysis of variance, ad hoc LSD (Least-Significance Difference), $p < 0.05$). Values are shown as means ± standard deviation ($n = 3$). DOC = dissolved organic carbon.

yield and DOC export), we compared the differences among the five forest types for individual years using one-way analysis of variance followed by least significant difference (LSD) post hoc comparisons. One-way analysis of variance followed by LSD post hoc comparisons was also used to examine the differences in plant species richness and diversity, and biomass among the five types of forests. The statistical analysis was conducted using R (R Foundation for Statistical Computing, Vienna, AT).

3. Results

3.1. ANR Significantly Reduced Surface Runoff, Sediment Yield, and DOC Export

The year immediately following the treatments, surface runoff from the young ANR stands was less than 50% of that from the young Chinese fir and *C. carlesii* plantations and was not different from the two mature

Table 1
Analysis of Variance Table for the Differences Among Forest Types in Runoff, Sediment Yield, Dissolved Organic Carbon, Species Richness, and Exponential of Shannon Entropy

	Degree of freedom	Sum square	*F*	*P*
	Runoff			
Year 1 runoff	4	7,586,235	12.9	<0.001
Year 2 runoff	4	2,754,411	15.2	<0.001
Year 3 runoff	4	3,357,956	4.6	0.023
	Sediment yield			
Year 1	4	2,287	3.3	0.056
Year 2	4	247	7.0	0.059
Year 3	4	6	3.0	0.072
	Dissolved organic carbon			
Year 1	4	466	26.2	<0.001
Year 2	4	88	19.3	<0.001
Year 3	4	57	5.0	0.018
Specie richness				
Tree layer	4	2,829	67.6	<0.001
Shrub layer	4	1,876	13.8	<0.001
Herb layer	4	920	1.8	0.198
	Exponential of Shannon entropy			
Tree layer	4	355	13.5	<0.001
Shrub layer	4	537	9.8	0.002
Herb layer	4	554	3.6	0.047

forests (Figure 3a and Table 1). Similarly, sediment yield was not different between the young ANR forest and the two mature forests starting from the first treatment year and all were 2 orders of magnitude lower than that in the two types of young plantations in the second treatment year and one order of magnitude lower in the third treatment year (Figure 3b and Table 1). DOC export through runoff from the young ANR stands was not different from the two mature forests, and it was approximately one third and one half of that exported from the young *C. carlesii* and Chinese fir plantations, respectively, in the first 2 years (Figure 3c and Table 1). By the third treatment year, DOC export from the young ANR stands was not different from that of the young Chinese fir stands but the young *C. carlesii* stands had higher DOC export than all other stands (Figure 3c and Table 1).

3.2. ANR Enhanced Plant Diversity

Three years after the treatments, the number of plant species of the tree layer in the young ANR stands was an order of magnitude greater than that in the two young forest plantations (Figure 3a). Moreover, it was not different from that of the two mature forests (Figure 4a and Table 1). Exponential of Shannon entropy of plants in the tree layer was not different between the young and the two mature forests, and all were much higher than that in the young *C. carlesii* and Chinese fir plantations (Figure 4b and Table 1).

Number of plant species in the shrub layer was greatest in the young ANR forest among the five forest stands and was approximately 2 times of that in the two young plantations (Figure 4b and Table 1). Moreover, it was greater than those in the two mature forests. Exponential of Shannon entropy of plants in the shrub layer was not different between the young ANR and the two mature forests, and all three were greater than those of the two young plantations (Figure 3b).

Number of plant species of the herbaceous layer was not different among the five types of forest stands, but exponential of Shannon entropy of the young ANR stands was smaller than that of other stands (Figure 4c and Table 1). However, the mature ANR forest had the largest number of species and exponential of Shannon entropy among all stands although the differences were mostly not significant (Figure 4c and Table 1).

3.3. ANR Accumulated 3–4 Times More Biomass Than Chinese Fir Plantation

Aboveground biomass of the young ANR forest was approximately 3 and 4 times of that in the young Chinese fir and *C. carlesii* plantations, respectively, although biomass of all the three treatments are still much lower than that of the two mature forests (Figure 5). Notably, aboveground biomass of the mature ANR forest was approximately 1.4 times of that of the nearby mature Chinese fir plantation of the same age.

4. Discussion

4.1. Surface Runoff, Sediment, and DOC Export

Forest floor and soil perturbation resulting from forest management practices such as harvesting and burning for site preparation are the key to surface runoff and the associated sediment yield and nutrient export (Grigal, 2000; Robichaud & Waldrop, 1994). The reduced surface runoff, sediment yield, and DOC export in the ANR forests than the two types of young monoculture forests likely resulted from the lower forest floor and soil perturbation in the ANR forests. Without burning for site preparation, ground vegetation was able to intercept, absorb (through roots), and transpire water thereby reducing surface runoff. The retention of forest residues following harvesting likely led to higher infiltration rate and water retention in forest floor mass in the young ANR forest than the two young plantations. Forest floor mass also reduces direct impact of rain drops on mineral soils, contributing to reduced soil erodibility. The reduced soil erodibility and surface runoff led to a smaller sediment production and DOC export. Although forest residues decompose gradually, the

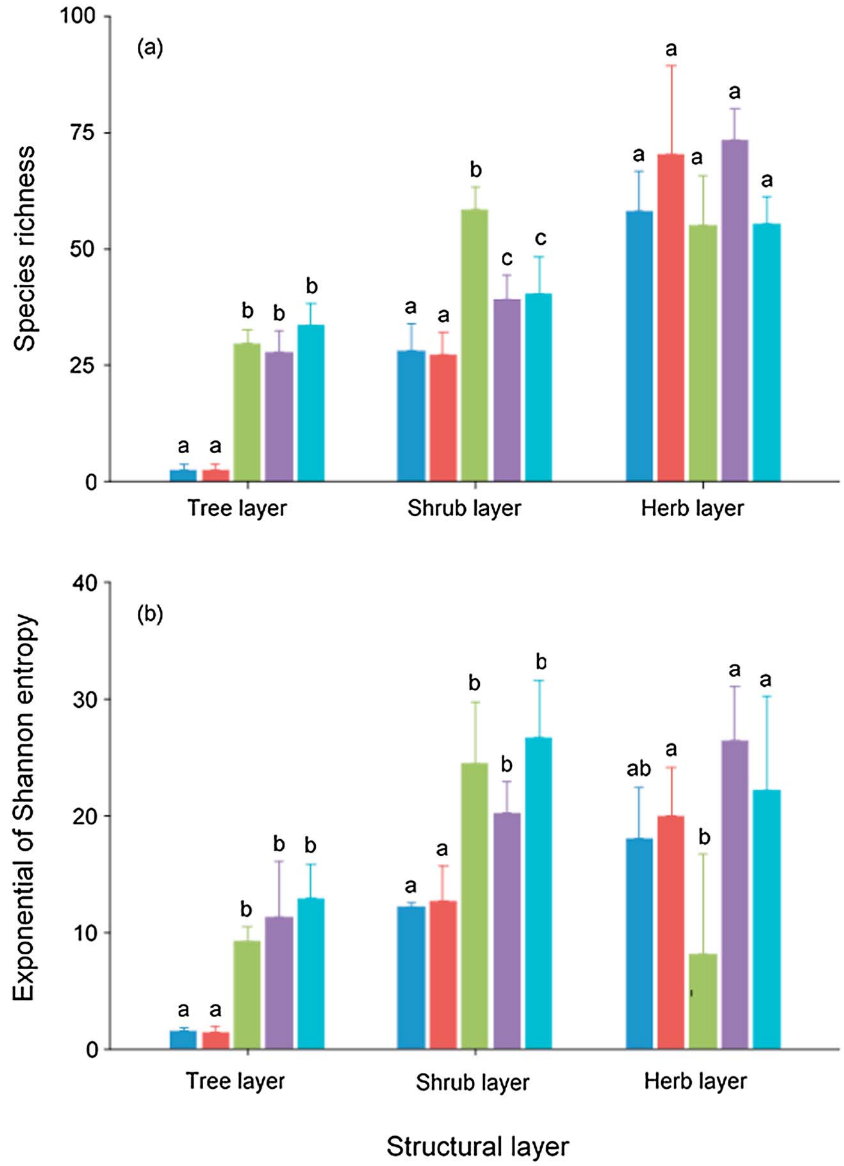

Figure 4. Species richness (a) and diversity (b) among three young and two mature forests. Bars of the same group sharing no common letter are statistically different (one-way analysis of variance, ad hoc LSD, $p < 0.05$). Values are shown as means ± standard deviation ($n = 3$).

rapid vegetation growth in the ANR forests produces more plant litter, which continue to contribute to reduce runoff, sediment yield, and DOC export in the ANR forests than in the monoculture plantations.

4.2. Plant Diversity

The lack of burning and weeding in ANR forests likely played an important role to their greater tree and shrub diversity relative to the young monoculture plantations (Figures 2b and 2c). Burning that is commonly prescribed in conventional Chinese fir plantation management and was also applied in the *C. carlesii* plots probably killed most seeds in the soil seed bank. Those that survived and germinated were removed by weeding in the first 3 years. In contrast, without burning the high light availability promotes the growth of many shade-intolerant species such as *Trema cannabina*, *Litsea cubeba*, and *Sapium discolor* in the young ANR plots following the treatment. The low diversity of plants in the herbaceous layer in the young ANR forest was most likely due to the very dense upper canopy (Figure 2d), which is not in favor of shade-intolerant species.

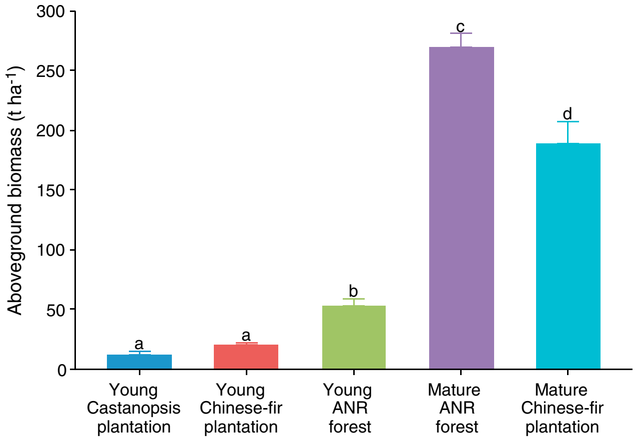

Figure 5. Aboveground biomass of the 3 year forests, a mature assisted natural regeneration forest, and a mature Chinese fir plantation. Bars sharing no common letter are statistically different (one-way analysis of variance, ad hoc LSD, $p < 0.05$). Values are shown as means ± standard deviation ($n = 3$).

However, this should be a short-live phenomenon; once self-thinning takes place, the diversity would recover as evident from the high diversity in the mature ANR forest.

4.3. Biomass and Carbon Sequestration

Several factors may contribute to the more rapid accumulation of biomass in the ANR forests than the monoculture plantations. First, the young ANR forests had much higher seedling densities than the young plantation forests, which undoubtedly result in greater biomass during early succession period. Second, the lack of burning preserved the seed bank and root systems, which enabled more efficient nutrient uptake in the young ANR during the growing season, especially in the first year following the treatment. Third, the greater tree diversity in the ANR forests than the monoculture plantations probably also contributed to its more rapid accumulation of biomass. The greater vegetation cover associated with more diverse species during the first few years after the treatment likely contributed to minimize nutrient leaching. This is important in the study region, which is characterized by abundant rainfall, steep slopes, and highly weathered soils with low availability of phosphorus and nutrient cations. The improved nutrient availability may contribute to the greater biomass accumulation we observed 3 years after the treatment. In later stages when trees are large, the more diverse tree species may use different proportions of resources (e.g., nutrients in different depth of the soil) and contributed to the greater biomass accumulation through the complementarity effect. Positive relationships between plant diversity and productivity have been widely reported (Erskine et al., 2006; Hector et al., 1999; Tilman et al., 1996; Van Ruijven & Berendse, 2003). A meta-analysis comparing tree growth in monocultures and mixed plantations illustrated that mixed plantations have larger diameter growth rate (Piotto, 2008). In humid tropics of Australia diverse plantations have been shown to achieve greater productivity than monocultures (Erskine et al., 2006). The greater accumulation of aboveground biomass in the ANR forests in turn led to greater litterfall production which also contributed to the greater aboveground biomass of the ANR forests than the monoculture plantations.

4.4. Implications for Large-Scale Management

As pointed out by Shono et al. (2007), in many degraded forestlands, natural regeneration in areas subjected to intensive anthropogenic disturbance is very slow due to factors such as soil degradation and isolation from intact forests. In such areas, weedy species such as shade-intolerant grasses may dominate for decades or even centuries (Shono et al., 2007). Our observations on several unmanaged lands following the harvest of Chinese fir plantations indicate that the unmanaged lands are covered by shrubs and herbaceous plants for more than one decade. The ANR management practices effectively facilitate the regeneration of secondary forests through reducing competition from weedy species and reserving sprouts and nutrient pools.

Chinese fir plantations are typically harvested at the age between 25 and 50 years. Assuming Chinese fir plantations would be replaced by ANR forest all at once, we used the 81 t ha^{-1} differences in aboveground biomass between the 34 year Chinese fir plantation and ANR forest, a 50% carbon content of the biomass, and 17×10^6 ha of Chinese fir plantations in China to estimate the additional aboveground carbon sequestration by plant biomass after 34 years of plantations, which is the age that many Chinese fir plantations are harvested. It showed that approximately 0.7 Pg more aboveground carbon will be sequestered in one rotation (i.e., 34 years; $81 \times 10^6 \times 17 \times 10^6 \times 0.5/10^{15} = 0.7$ Pg). In addition, using the 8.4 kg ha^{-1} (5.6 kg in the first year and 2.8 kg in the second year) differences in DOC export between the young Chinese fir plantation and the young ANR forest in the first 2 years (when the differences were significant), an additional 0.14 Tg of DOC will be retained in the ANR forests if all Chinese fir plantations in China were replaced by the ANR forests. On a global scale, approximately 8.4 Pg of carbon is emitted through combustion of fossil fuels in 2009 (Friedlingstein et al., 2010). Our estimate indicates that replacing conventional Chinese fir plantations in China alone could have a substantial potential to mitigate increases in atmosphere CO_2 resulting from fossil fuel combustion.

5. Conclusions

Through a comprehensive manipulation experiment, we demonstrate that immediately following forest harvesting, the greater soil and water conservation under ANR treatment, as evident from the smaller runoff, sediment yield, and DOC export, facilitates the establishment and growth of a diverse plant species in the young ANR forest. The greater structural diversity resulting from higher plant diversity in turn helps to reduce surface runoff, sediment yield, and DOC export in this otherwise highly erodible region. Therefore, the results suggest that ANR triggers positive feedbacks among soil and water conservation, biodiversity protection, and biomass accumulation and thereby enhance ecosystem services.

We acknowledge that our experiment represents results from one location and the magnitude of differences between ANR forests and conventional Chinese fir plantations may vary in different locations due to differences in climate, soil conditions, and other management practices (e.g., fertilization). In addition, it is unlikely to replace all the Chinese fir plantations in China. Also, there are likely differences between establishing an ANR forest from an existing ANR forest and establishing an ANR forest from a managed monoculture Chinese fir plantation. However, this study clearly illustrates tremendous potential of ANR as a forest management option for maximizing forest carbon sink and other ecosystem services in China and across the globe.

Acknowledgments
The study was supported by grants from National Natural Science Foundation of China (grant 31130013) and National Natural Science Foundation of China (grant U1505233). L. W. acknowledges partial support from Division of Earth Sciences of National Science Foundation (EAR-1554894) and from the Agriculture and Food Research Initiative program (2017-67013-26191) of the USDA National Institute of Food and Agriculture. The authors declare no conflict of interest. Data of this paper are deposited at Dryad Digital Repository (doi:10.5061/dryad.5qv78r3). Additional supporting information may be found in the online version of this article.

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